Emittance improvements of CW photoinjector by ellipsoidal shaping

Content:

- Motivation
- Proj. emittance decomposition of photoinjector
- CW photoinjector layout and performance
- Ellipsoidal shaping effect for CW injector at 100 pC
- Discussions
- Summary & outlook

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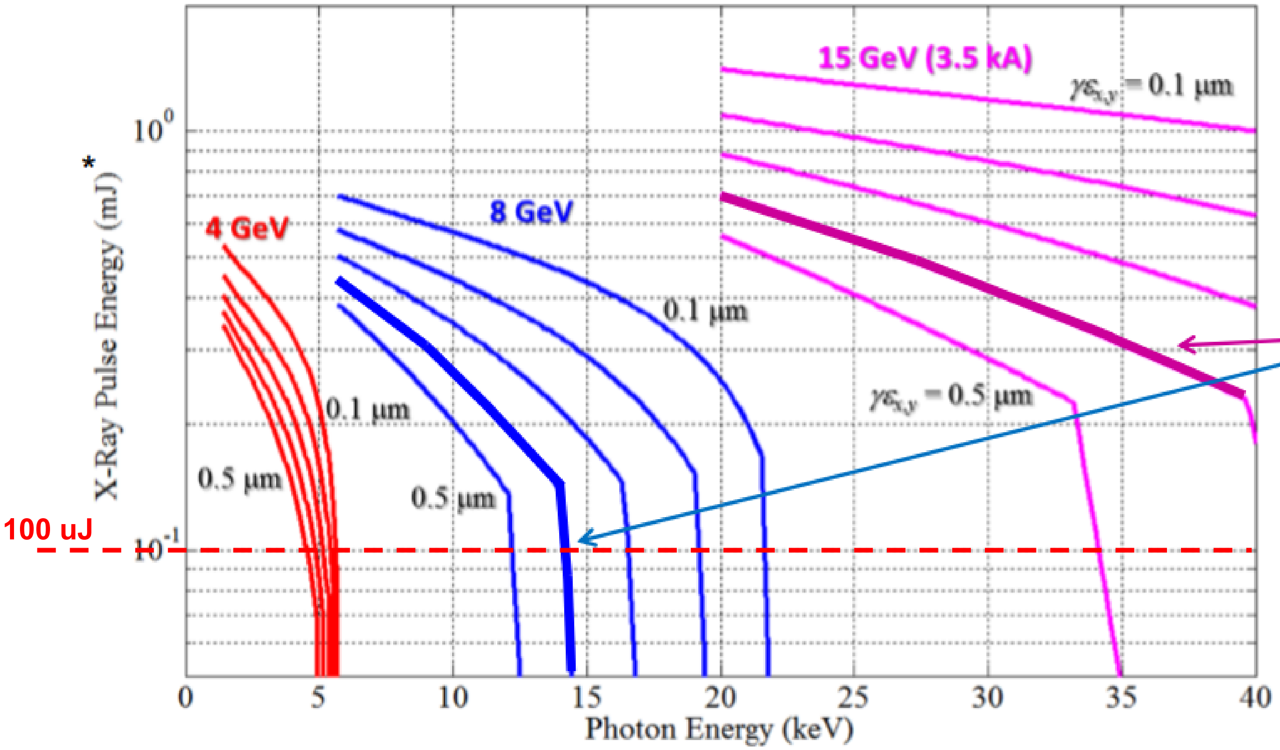
09.11.17, PITZ Physics Seminar

Motivations

Injector R&D Program

Big impact of improved injectors for LCLS-II CuRF and LCLS-II-HE SCRF, extending SCRF reach out beyond 20 keV



Baseline injector

[redacted]

Injector R&D aimed at

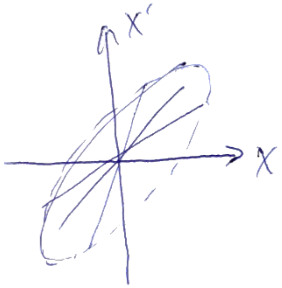
[redacted]

Parameter	Nominal operation	
Bunch charge	200 pC	≥100 pC
Normalized emittance	0.4 µm	≤0.1 µm
Pulse length (rms)	3 psec	2 psec
Slice energy spread (rms)	1 keV	1 keV

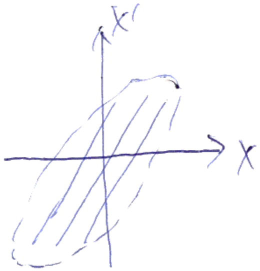
Projected emittance decomposition

- C. Mitchell, arXiv:1509.04765
  - Average slice emittance
  - Emittance due to slice twiss parameter mismatch
  - Emittance due to slice centroid misalignment

$$\varepsilon_{100\%} = \sqrt{\varepsilon_{slice}^2 + \Delta\varepsilon_{mismatch}^2 + \Delta\varepsilon_{misalign}^2}$$



Mismatch emittance



Misalignment emittance

- For ideal photoinjecotor simulations
  - no beam-beamline misalignment, no RF coupler kick

$$\varepsilon_{100\%} = \sqrt{\varepsilon_{slice}^2 + \Delta\varepsilon_{mismatch}^2}$$

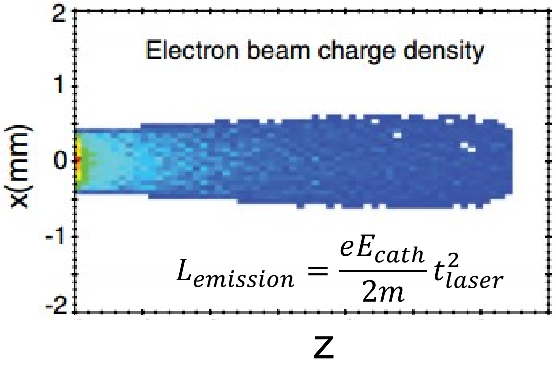
$$\varepsilon_{slice} = \sqrt{\varepsilon_{th}^2 + \Delta\varepsilon_{slice}^2}$$

Transverse beam brightness of photoinjector

- Maximize photoemission beam brightness at cathode

$$B_\perp^{pancake} \sim \frac{Q}{\varepsilon_x \varepsilon_y} \propto \frac{E_0}{\sigma_{p_\perp}^2}$$

$$B_\perp^{cigar} \propto \frac{E_0^{3/2} t_{laser}}{\sqrt{R}\sigma_{p_\perp}^2}$$



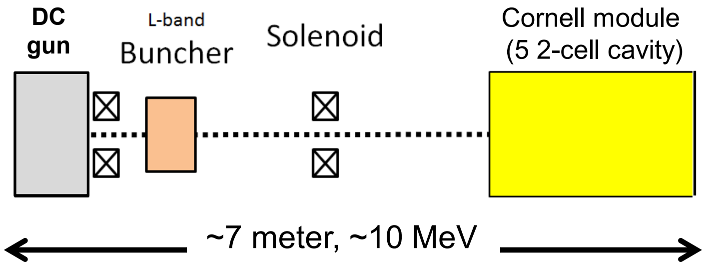
  - High gun gradient
  - low thermal emittance cathode
  - Laser BSA and pulse length tuning

- CW gun VS pulsed gun: **5-20** MV/m vs **60-120** MV/m
  - Improve CW gun gradient: targeting **20-40** MV/m
  - Cigar photoemission (**40-60** ps)
    - trade peak current for transverse emittance
  - Low thermal emittance photocathodes with ~ps second response time
    - Reduce energy gap between photon energy and ‘work function’
    - Reduce cathode surface roughness
    - Cool cathode to cryo temperature

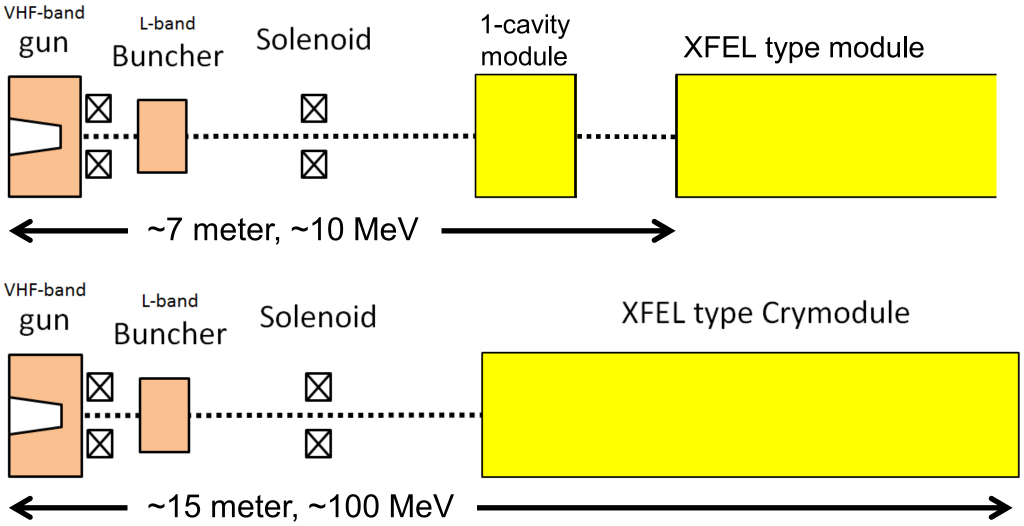
Transverse beam brightness of photoinjector

- Conservation of photoemission beam brightness
  - Emittance growth from slice mismatch: emittance compensation
    - gun drift optimization, solenoid scan, booster gradient scan…
  - Emittance growth from slice misalignment: slice dependent dipole kick
    - laser BBA, solenoid alignment, booster steering free, gun coupler kick…
  - Slice emittance growth
    - Nonlinear space charge effect
    - X & Y phase space coupling
      - Minimize quad field error in solenoid or RF field asymmetry
    - Solenoid spherical aberration: $\delta\epsilon \propto \sigma_{beam}^4$
    - …
- CW gun VS pulsed gun: **0.4 - 4** MV vs **4 - 6** MV
  - Higher space charge effect: Gaussian laser → flattop → ellipsoidal?
  - Larger beam size
    - Solenoid aberration
      - improve beam focusing, improve solenoid design
    - Emittance growth more sensitive to all practical errors

CW photoinjector layouts



Cornell DC gun injector
(300 ~500 kV)

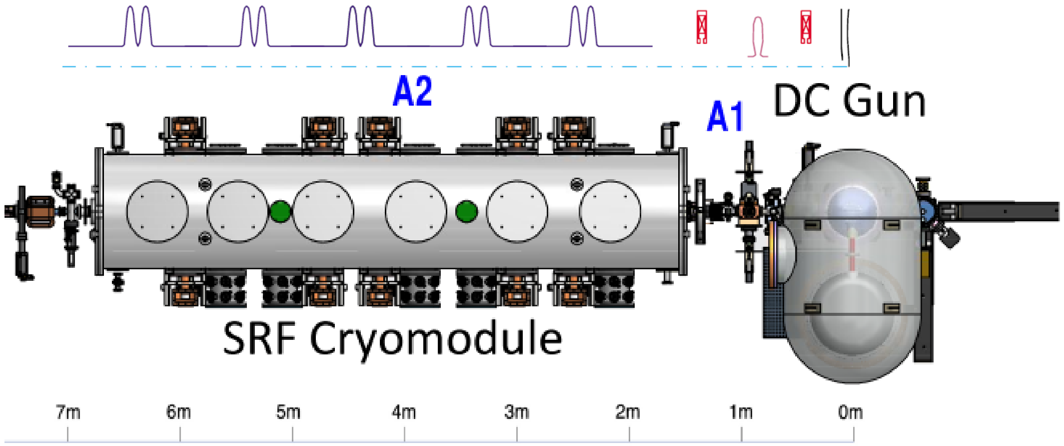


LCLS-II VHF gun injector
(~750 kV)

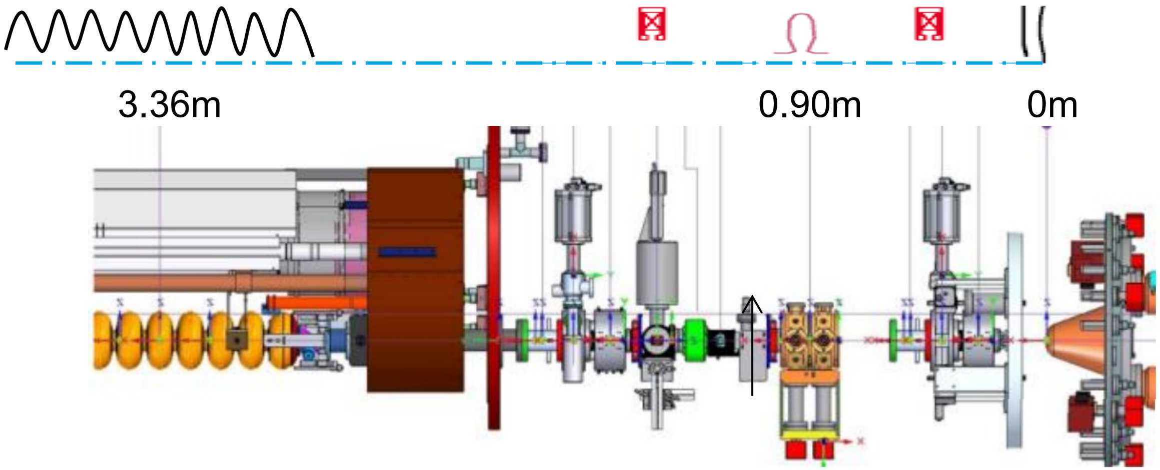
HZDR SRF gun injector
(few MeV)

CW photoinjector layouts

- DC gun photoinjector (Jlab, Cornell)



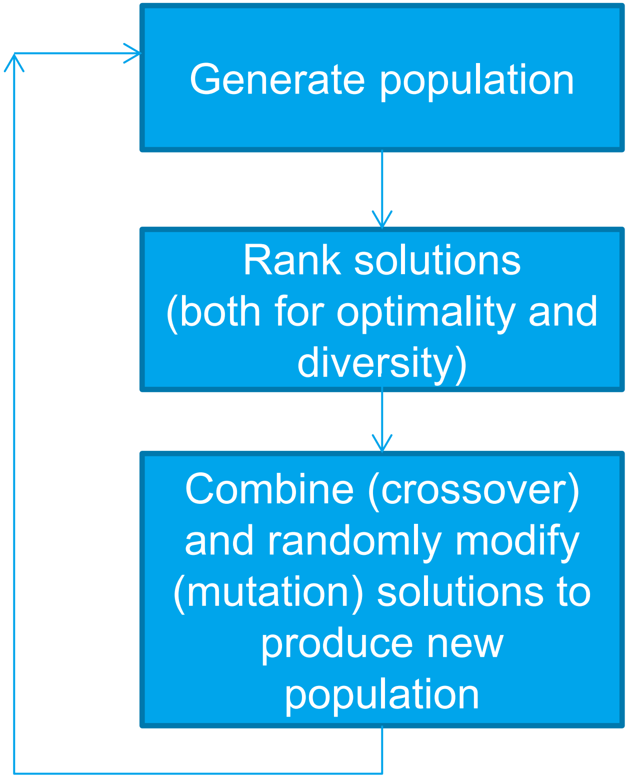
- NC VHF gun photoinjector (LCLS-II)



CW injector optimizations

- Pulsed injector optimizations:
  - Beam peak current → Laser pulse length
  - Injector layout → Emittance oscillation scan → Solenoid strength, drift length
  - Min emittance scan → Laser BSA
- CW injector based on DC gun and VHF gun
  - Beam peak current → Laser pulse length, buncher location, voltage & phase
  - Injector layout → Emittance oscillation scan → two solenoids, different ways of beam peak current
  - Min emittance scan → Laser BSA
- Tuning knobs
  - Pulsed injector (7): laser(2), gun(1), solenoid(1), booster(2)
  - CW injector with buncher (13): laser(2), gun(1), solenoid(3), buncher(3), booster(4)

Multi-Objective Genetic Optimizer (MOGA)

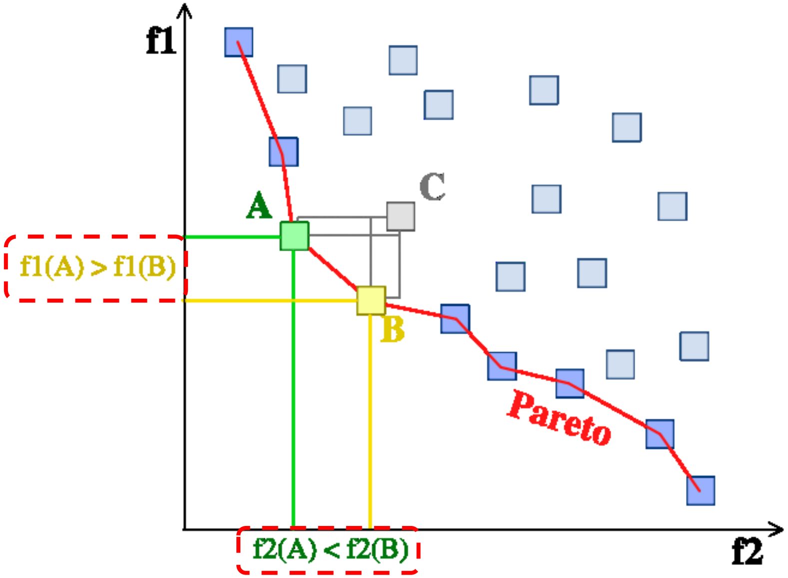


Generate population

Rank solutions (both for optimality and diversity)

Combine (crossover) and randomly modify (mutation) solutions to produce new population

- A and B dominate C, but A and B don't dominate each other.
- The algorithm finds a front of non-dominated solutions.
- The final result is not a single solution



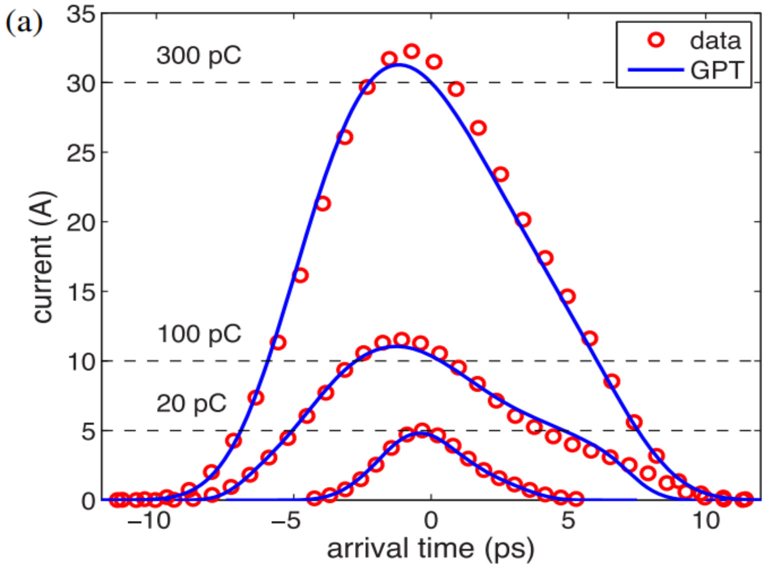
APEX has developed an optimization tool based on NSGA-II (Non-dominated Sorting Genetic Algorithm II)

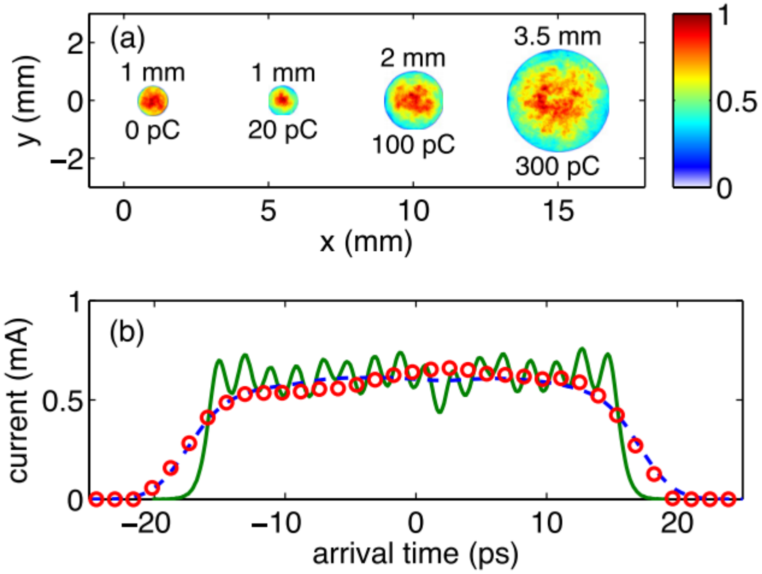
Description of NSGA-II can be found in http://www.iitk.ac.in/kangal/Deb_NSGA-II.pdf

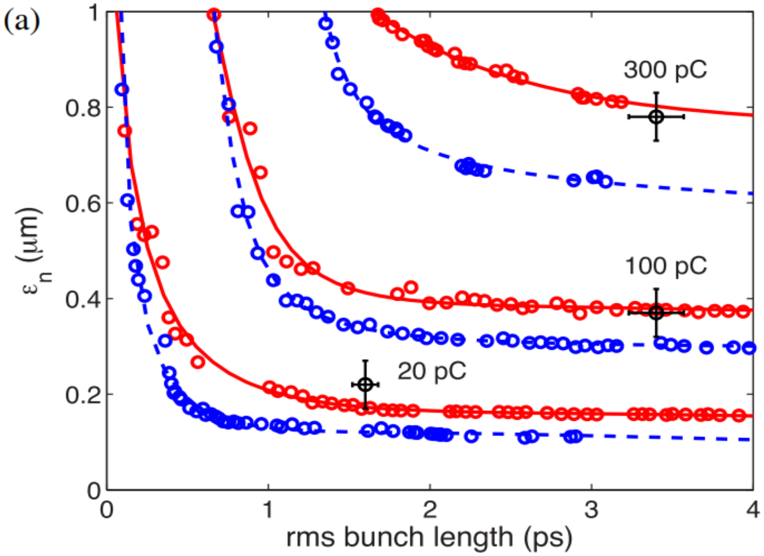
Current state of the arts performance

- Cornell injector measurements
  - 395 kV (4 ~ 8 MV/m)
  - NaKSb, 520 nm, ~0.52 um.rad/mm

Q (pC)	100% ϵ_n	95% ϵ_n	Cathode ϵ_n
20	0.22 (0.24)	0.18 (0.19)	0.12 (0.11)
100	0.37 (0.39)	0.30 (0.32)	0.24 (0.23)
300	0.78 (0.78)	0.62 (0.60)	0.42 (0.41)

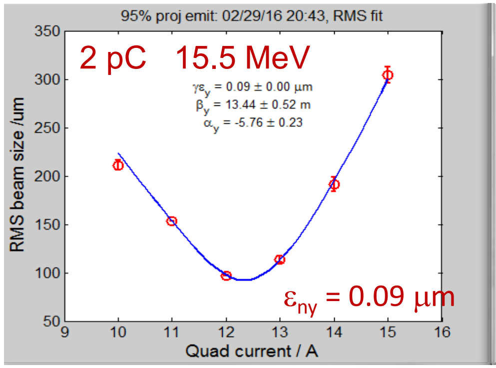


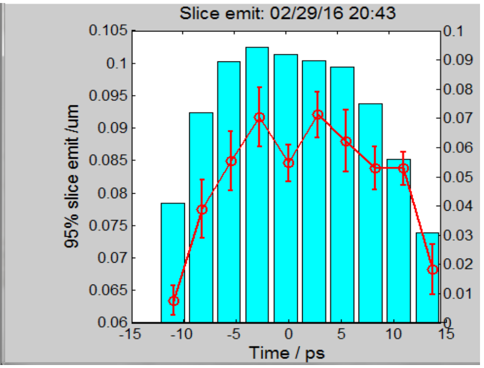




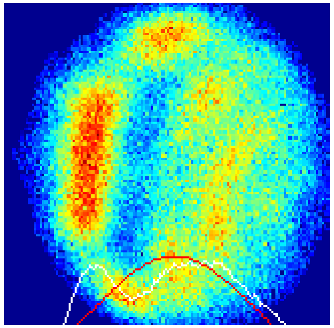
Current state of the arts performance

- APEX photoinjector (as of 2016.03)
  - Thermal emittance at 20 MV/m
    - K_2CsSb, 515 nm: 0.5-0.6 um.rad/mm rms
    - Cs2Te, 266 nm: ~0.7 um.rad/mm





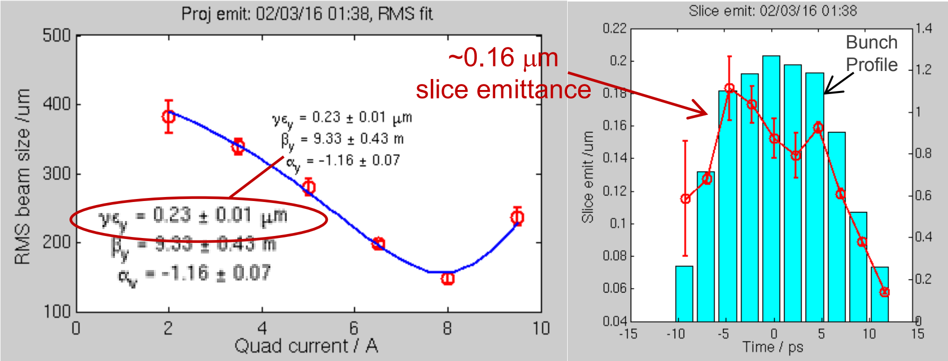
Laser



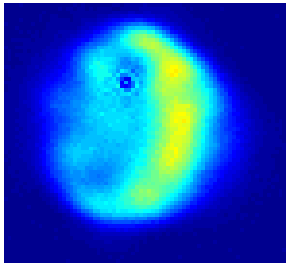
  - 20 pC measurement

20 pC, 15.4 MeV, 95% Projected emittance

95% Slice emittance



Laser



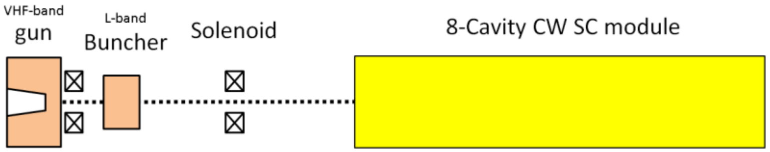
Emittance improvement of CW photoinjector

- Higher gradient and higher gun voltage
  - NC cavity: bigger cavity with lower frequency, 100~130 kW (APEX)
  - SRF cavity: L-band or VHF-band
- Low thermal emittance cathode
- Laser shaping
  - Flattop shaping → Ellipsoidal shaping
- Solenoid spherical aberration
  - Better beam focusing
  - Better solenoid design
- …

Photoinjector optimization setup

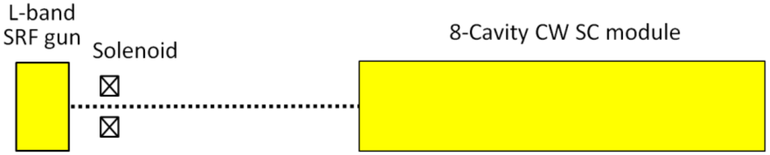
- Simulation setup for 100 pC
  - Flattop laser (2 ps rise time) vs Ellipsoidal laser
  - NC VHF band gun based injector

Laser	radius and duration variable
gun	20 MV/m, 750 kV, phase variable
buncher	<240 kV, voltage and variable variable
solenoid 1&2	strength variable (APEX solenoid)
module	phase fixed to crest acceleration 1 & 4 variable, 2 & 3 off, 5-8 fixed to 32 MV/m
layout	Using LCLS-II injector layout



  - SC L band gun based injector (no dedicated velocity compression)

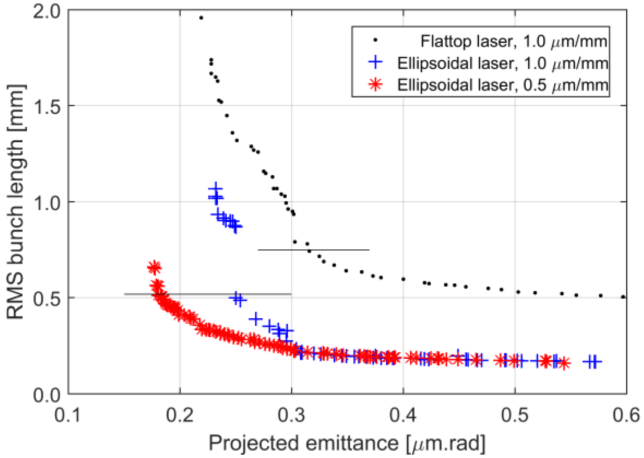
Laser	radius and duration variable
1.5 cell gun	40 MV/m, MMMG phase
solenoid	Strength variable (HZDR solenoid)
module	phase fixed to crest acceleration 1 & 4 variable, 2 & 3 off, 5-8 fixed to 32 MV/m
layout	SC solenoid 0.5 m (HZB), cavity #1 center at 4.5 m



NC VHF band gun

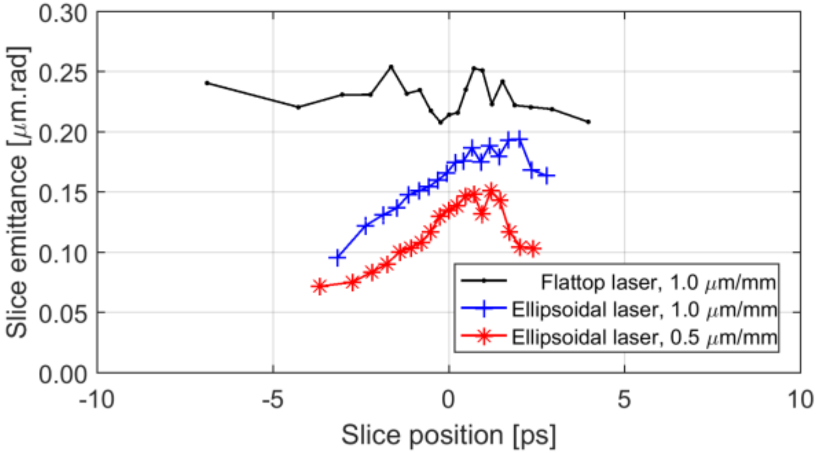
> Comparison between flattop and ellipsoidal laser

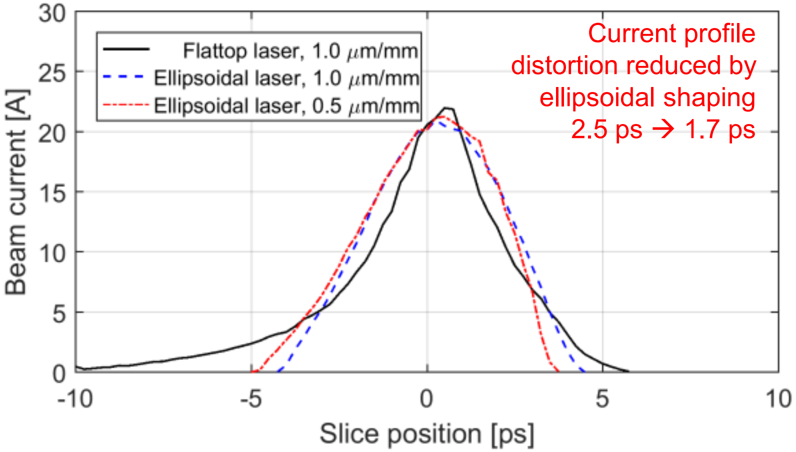
- Flattop → ellipsoidal shaping : 33% reduction on emittance (100 pC, 20 A)
- Need both ellipsoidal shaping and better cathodes to achieve 0.1 um.rad



	Flattop 1 µm/mm	Ellipsoidal 1 µm/mm	Ellipsoidal 0.5 µm/mm	Unit
$\varepsilon_{100\%}$	0.28	0.19	0.12	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
ε_{th}	0.18	0.14	0.09	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
$\Delta\varepsilon_{mis}$	0.16	0.09	0.04	µm

$$\varepsilon_{100\%} = \sqrt{\varepsilon_{th}^2 + \Delta\varepsilon_{slice}^2 + \Delta\varepsilon_{mis}^2}$$



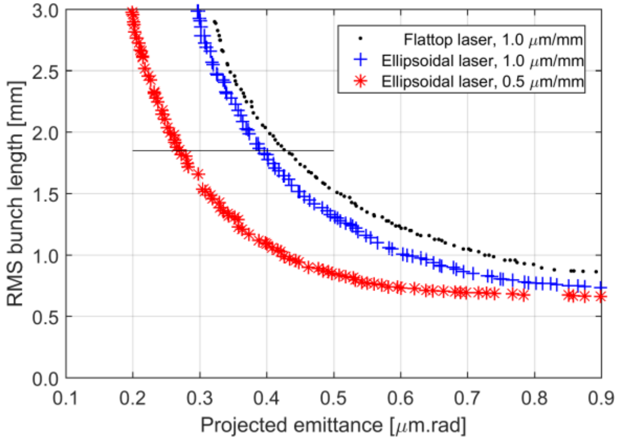


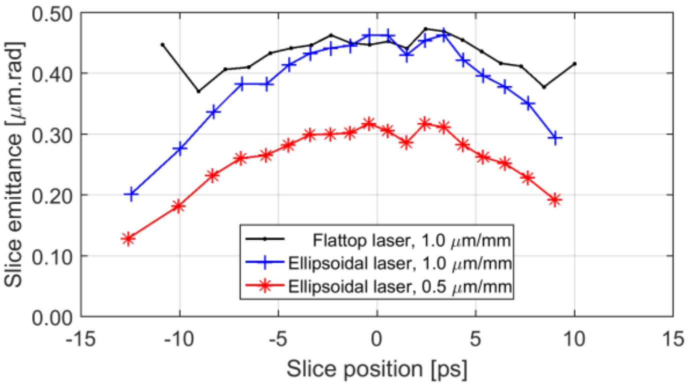
Current profile distortion reduced by ellipsoidal shaping 2.5 ps → 1.7 ps

SC L band gun

> Comparison between flattop and ellipsoidal laser

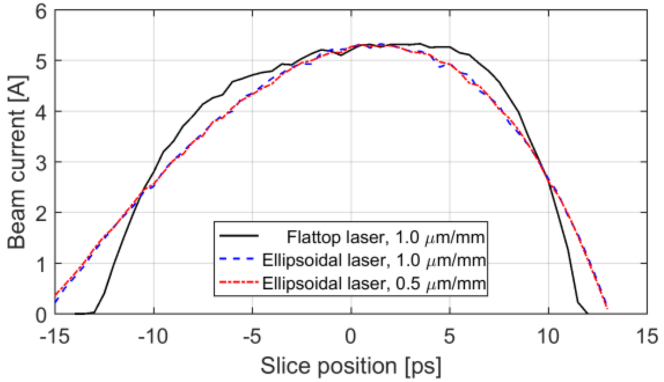
- Flattop → ellipsoidal shaping: 10% reduction on emittance (100 pC, 5 A)
- Better cathode (1 → 0.5 um.rad): 32% reduction on emittance





	Flattop 1 µm/mm	Ellipsoidal 1 µm/mm	Ellipsoidal 0.5 µm/mm	Unit
$\varepsilon_{100\%}$	0.44	0.39	0.26	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
ε_{th}	0.28	0.28	0.18	µm
[redacted]	[redacted]	[redacted]	[redacted]	µm
$\Delta\varepsilon_{mis}$	0.08	0.05	0.03	µm

$$\varepsilon_{100\%} = \sqrt{\varepsilon_{th}^2 + \Delta\varepsilon_{slice}^2 + \Delta\varepsilon_{mis}^2}$$



Solenoid abberation

Solenoid spherical abberation

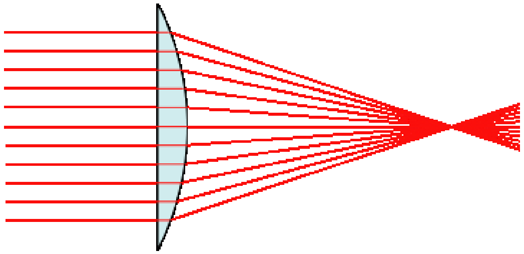
- 3rd order effect $r' = \left(\frac{1}{f}\right)_{\mathrm{sol}} r + \alpha r^3$

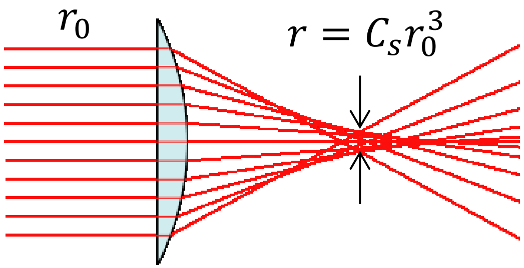
Focusing strength

$$\left(\frac{1}{f}\right)_{\mathrm{sol}} = \left(\frac{e}{2mc\beta\gamma}\right)^2 \int B_z^2 dz$$

Spherical abberation

$$\alpha = \frac{1}{4}\left(\frac{e}{2mc\beta\gamma}\right)^2 \int \left(\frac{\partial B}{\partial z}\right)^2 dz$$





- Spherical abberation $C_s = \frac{2\alpha}{1/f}$

$$C_\mathrm{s} = \left(\frac{1}{2}\int_{-\infty}^{+\infty} B_z'^2 \mathrm{d}z\right) \Big/ \left(\int_{-\infty}^{+\infty} B_z^2 \mathrm{d}z\right)$$

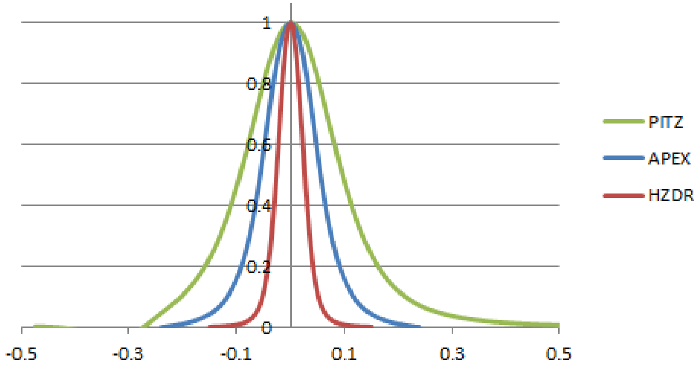
Assuming solenoid model

$$B_z(z) = B_\mathrm{o}\left(\frac{1}{1+(z/a)^n}\right) \Rightarrow C_{\mathrm{s},n} = \frac{(n+1)}{12}\frac{1}{a^2}$$

$2a$ ~ FWHM of solenoid field
→ bigger bore, or longer
n ~ sharpness of fringe field slope
→ remove cap

- Solenoid comparison

PITZ $C_s = 33\, m^{-2}$
APEX $C_s = 99\, m^{-2}$
HZDR $C_s = 466\, m^{-2}$



Solenoid abberation

- Emittance growth $\Delta\varepsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2} = \kappa\alpha\sigma_x^4 = \frac{\kappa}{2f}C_s\sigma_x^4$
  - Gaussian distribution $\kappa = \sqrt{6} \approx 2.4$
  - Ellipsoidal distribution $\kappa = \sqrt{\frac{200}{147}} \approx 1.2$
  - Uniform distribution $\kappa = 1$
- Emittance growth evaluation (flattop laser, 1 um.rad/mm case)
  - SC gun + HZDR solenoid APEX gun + APEX solenoid

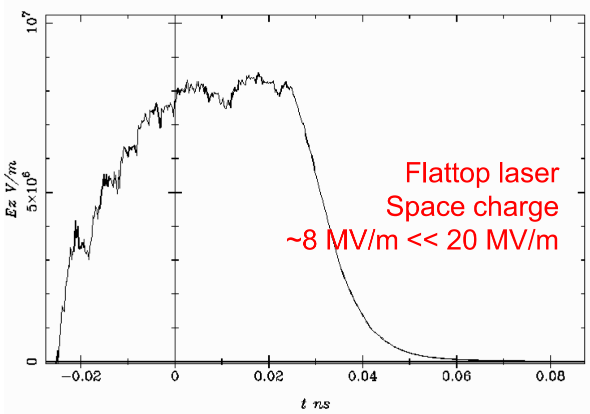
RMS beam size at solenoid	2.5	3.5	mm
Gaussian distribution	0.40	0.20	mm.mrad
Ellipsoidal distribution	**0.19**	**0.10**	mm.mrad
Uniform distribtuion	0.16	0.08	mm.mrad
Real distribution	0.20	N/A	mm.mrad
Emittance decomposition	0.33	0.15	mm.mrad

I. Bazarov et al, Phys. Rev. ST Accel. Beams **14**, 072001

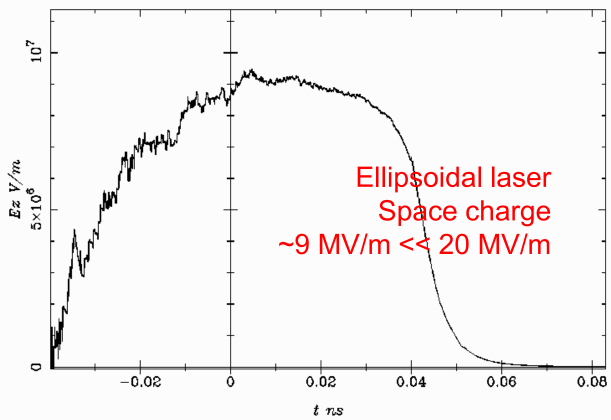
Photoemission in CW guns

- Cathode space charge field during photoemission

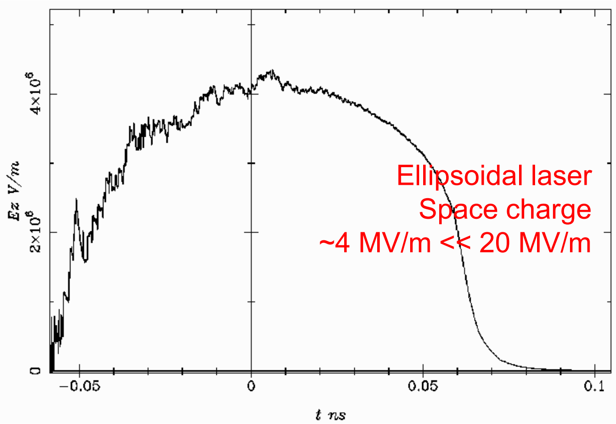
APEX gun injector (100 pC)



Flattop laser
Space charge
~8 MV/m << 20 MV/m

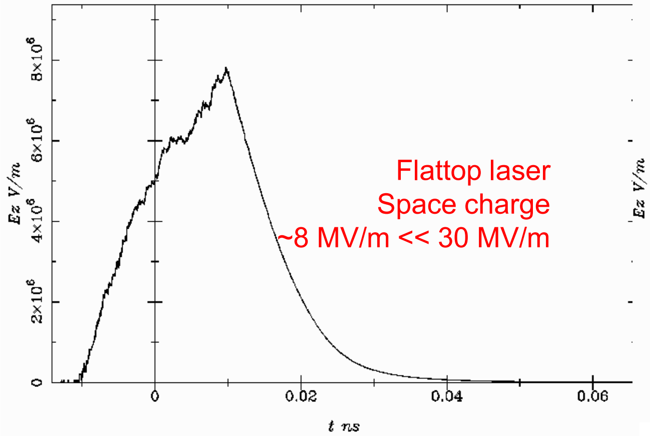


Ellipsoidal laser
Space charge
~9 MV/m << 20 MV/m

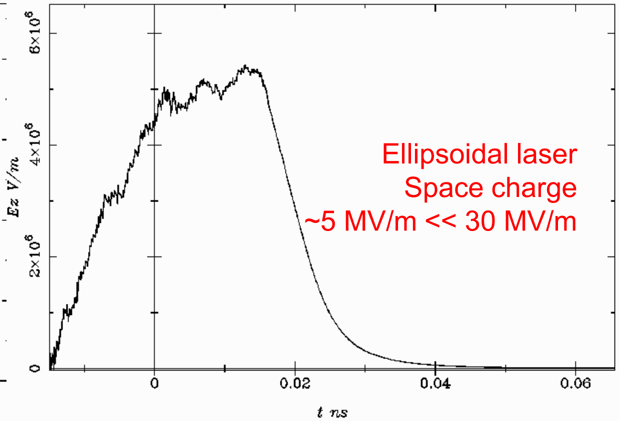


Ellipsoidal laser
Space charge
~4 MV/m << 20 MV/m

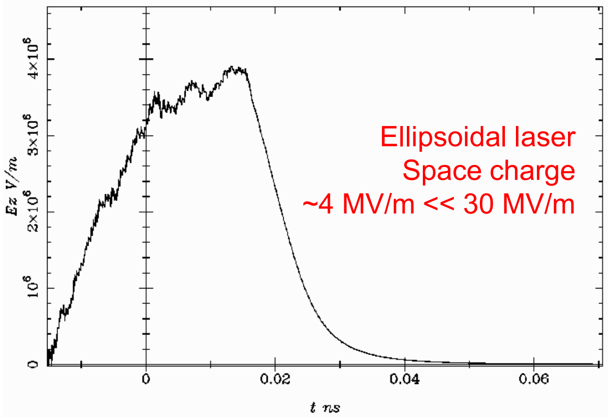
SC gun injector (100 pC)



Flattop laser
Space charge
~8 MV/m << 30 MV/m



Ellipsoidal laser
Space charge
~5 MV/m << 30 MV/m



Ellipsoidal laser
Space charge
~4 MV/m << 30 MV/m

Photoemission in all cases are not close to saturation!

What is limiting beam brightness at cathode?

Summary

- For NC VHF gun (20 MV/m) based injector
  - Ellipsoidal shaping improves 100 pC beam emittance by 33%
  - 0.1 um.rad, 20 A beam is possible with current gun if both ellipsoidal shaping and low thermal emittance cathode are available.
- For L-band SC gun (40 MV/m) based injector
  - HZDR solenoid spherical abberation is big.
  - Ellipsoidal shaping effect is not clear, further injector optimizations are needed.
- In contrast to pulsed high gradient injectors, optimized solutions of CW injectors are not close to photoemission saturation.
- Slice emittance growth in CW injector should be analyzed in more details.